GAS TURBINE AND JET ENGINE FUELS

PROGRESS REPORT NO. 5

NAVY CONTRACT N 600(19)58219

FEBRUARY, 1963

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PHILLIPS 66

PHILLIPS PETROLEUM COMPANY

PHILLIPS PETROLEUM COMPANY - RESEARCH DIVISION REPORT 3449-63R
Feature No. 6045
April 4, 1963

Progress Report No. 5
Navy Contract N600(19)-58219

GAS TURBINE AND JET ENGINE FUELS

By

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W. L. Streets

SUMMARY

The fifth bimonthly period under Navy Contract N600(19)-58219 has been utilized in continuing the study of the effects of sulfur on the durability of several typical jet engine "hot section" alloys. The Phillips 2-Inch Research Combustor facility has been shut down during this period for installation of greater air preheating capacity. Consequently, efforts were directed to a bench-scale study of sulfur corrosion of the type known colloquially as "black plague". A semi-dynamic furnace test procedure was employed. Superalloys, including Udimet 500, René 41, Hastelloy R-235, Waspalloy and Haynes Alloy 25, have been evaluated. These test were carried out at 2000 F with various combinations of air, sulfur dioxide, carbon and sea salts present. The objectives were: (1) to reproduce the type of attack described by other investigators and (2) to assess the relative importance of the several factors postulated as responsible for the attack. Other investigators have attributed this attack to unburned carbon, ingested sea salts and/or fuel sulfur. The results indicate that: (1) attack of the type described in the literature was reproduced; (2) metal loss was not a wholly reliable index to degree of attack; (3) degree of attack was shown to be potentially catastrophic; (4) of the individual corrodents, only sea salt increased the attack above the "air only" baseline; (5) the effect of sea salt alone and in combination with carbon and/or SO_2 was specific to alloy type; (6) carbon, as a possible reducing agent for protective chromium oxide films, was confirmed as detrimental to all the alloys in tests with SO_2 and air; (7) carbon accelerated sea salt corrosion of three of the alloys and markedly inhibited sea salt corrosion of the other two alloys; (8) when sulfur was present as both sea salts and SO_2 (no carbon) results varied from mild acceleration by the added SO_2 with Udimet 500 to pronounced inhibition with René 41, although the R-41 was still badly corroded; (9) when carbon was included while supplying both SO_2 and sea salts the attack was accelerated except for René 41 where, again, attack was apparently inhibited by the carbon and SO_2; (10) except for R-41, corrosion was catastrophic with air + carbon + SO_2 + sea salt; (12) checks for magnetic properties in scale

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removed from each test strip showed that all were non-magnetic; (13) a number of test strips became strongly magnetic following exposure, suggesting that some enrichment in nickel and/or cobalt may have occurred by virtue of losses in the non-magnetic alloying metals.

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Research Division Report 3449-63R

PHILLIPS PETROLEUM COMPANY

BARTLESVILLE, OKLAHOMA

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I. INTRODUCTION

The fifth bimonthly period under Navy Contract N600(19)-58219, December, 1962 through January, 1963, has been spent continuing the study of the effects of sulfur on the durability of several typical jet engine "hot section" alloys. The Phillips 2-Inch Research Combustor has been shut down during this period for extensive modifications to permit greater air preheating. Efforts during this period have therefore involved an investigation, in bench-scale apparatus, of sulfur corrosion of the type which has come to be known colloquially as "black plague". Since corrosive attack of the type identified by other investigators (1,2) as black plague had not been observed in this laboratory during repeated combustor testing in which sulfur was present both in the fuel and in ingested sea water (Na_2SO_4), it was considered desirable to attempt to reproduce this type of corrosion under the conditions described by these investigators in order to better understand its nature, appearance, and the relative importance of the variables suggested as responsible for the attack. For this purpose a semi-dynamic furnace test procedure patterned after one described by Bristol Siddely Engines, Ltd. has been employed. A group of superalloys, including Udimet 500, René 41, Hastelloy R-235, Waspalloy and Haynes Alloy 25 (L 605), has been evaluated at 2000 F in the presence of air, sulfur dioxide, carbon and sea salts, individually and in all combinations.

Black plague sulfur attack has been pictured by some investigators (1) as a current problem in aviation gas turbines, although this has not been confirmed during discussions with personnel familiar with both Navy and Air

Force aircraft field experience in the United States. Nevertheless, a number of laboratory investigations do suggest that this is a potential problem. It therefore appears desirable to more closely define the causative factors, possible means of avoidance, and the relative performance of the various available alloys.

II. TEST METHODS AND APPARATUS

The bench-scale method employed for this investigation was patterned after a method described by Bristol Siddely Engines, Limited (1). In the Phillips version, metal specimens measuring 1/2-inch wide by 2 3/8-inch long by 1/16-inch thick are placed in porcelain boats 3/8-inch wide by 3-inch long by 1/4-inch deep. The boat containing the metal strip is placed in a 2-inch tube furnace held at 2000 F. Air is flowed through the furnace for a period of 45 minutes followed by sulfur dioxide for 45 minutes. These gases are cycled 45 minutes each for a total duration of six hours. For tests involving the possible reducing effects of carbon, a 1/2-inch diameter by 2-inches long carbon rod is placed in the boat along side the metal strip and in contact with the surface of the strip. The tests which include sea salt are carried out by simply packing 2 grams of the salt around the metal specimen as it sits in the porcelain boat. The sea salt is prepared by blending dry salts together in the proportions specified in ASTM Method D665-60 for synthetic sea water. The salts used and their relative proportions are as follows:

Component	Per Cent by Weight
$NaCl$	58.49
$MgCl_2 \cdot 6H_2O$	26.46
Na_2SO_4	9.75
$CaCl_2$	2.76
KCl	1.64
$NaHCO_3$	0.48
KBr	0.24
H_3BO_3	0.07
$SrCl_2 \cdot 6H_2O$	0.10
NaF	0.01

In cases where sulfur dioxide is not used, air is continuously flowed through the furnace for the entire six-hour duration.

Evaluation of the extent of attack is based upon weight of metal lost (following rotary brush descaling) and on visual observations. In cases where scaling was sufficient, samples of the scale were retained for possible later analysis. These tests were run on each of the five superalloys with combinations of materials as follows: (1) air, (2) air + carbon, (3) air + sulfur dioxide, (4) air + sea salt, (5) air + carbon + sulfur dioxide, (6) air + sulfur dioxide + sea salt, (7) air + carbon + sea salt, and (8) air + carbon + sulfur dioxide + sea salt.

This test method is admittedly severe as compared to actual conditions existing in engines. However, since the intent here is simply to demonstrate potentialities and to establish the relative importance of the several simulated fuel and/or air contaminants, it is believed to be a useful tool for the purpose.

III. BACKGROUND INFORMATION ON "BLACK PLAGUE" SULFUR ATTACK AS OBTAINED FROM THE LITERATURE

A. Visual Appearance

Black plague sulfur attack, as described in the literature (1,2), is evidenced by dark-colored, raised blisters on the surface of the component. A green coloration may be present. In severe cases the raised attack may be nodular and possibly, in the case of a turbine blade, cover the whole of the concave side in the hottest region of the blade. Cracks may then appear in the area of sulfur attack itself, for example, longitudinally on the leading edge or in a transverse direction at the trailing edge. These cracks may be restricted with little or no penetration into the sound core material.

A remarkable feature of this type of attack is that turbine blades have, on occasion, suffered extremely severe attack without failure. This is attributed to the tendency of sulfur attack to advance on a broad front and hence it is by thinning of the sections until the component is unable to withstand the applied stress that failure may ultimately occur, rather than by preferential attack of the stress corrosion type on the grain boundaries.

B. Microscopic Appearance

The microscopic appearance of sulfur attack has been described (1) by characteristic phases, although all phases may not always be detected. The following phases have been reported:

1. In front of the advancing corrosion products, light gray globules are evident. These are generally randomly distributed within the grains although they may also be in the grain boundaries if carbides have been precipitated, since these are rather susceptible to attack.
2. There follows a two phase region consisting of a light "metallic" phase intermingled with a darker gray material.

3. A mainly continuous zone, which is gray in appearance, is produced on the outer surface.

4. In laboratory experiments a phase which has apparently been liquid may also exude to the surface.

C. Chemical Composition

Although little concrete information is available, one reference (1) indicates that the metallic elements are present in the scale in the same relative proportions as in the parent material. Reports regarding the presence of sulfur on corroded blades produced by actual engine tests are rather variable, ranging from 0.5 per cent to slight or undectable (1,2). It has been demonstrated that the outermost layer of corrosion may have only a small sulfur content but that this may increase nearer the base metal.

D. Physical Characteristics

The corrosion product has been reported to be very hard and brittle. It is adherent and occupies a considerably larger volume than the base material. Only after it has become quite thick does it tend to crack and chip away under engine running conditions. It may sometimes be removed by vapor blasting or shot blasting, whereupon pitting may result.

X-ray diffraction analyses (1) have generally shown that the corrosion product consists predominantly of nickel oxide (NiO) together with a spinel of mainly nickel oxide and chromium oxide.

Sulfide has been detected on turbine blades using a technique of electron probe analysis. Evidence of sulfide has been found at the metal/oxide interface and a concentration of chromium at the grain boundaries. Titanium/molybdenum inclusions have been found away from the interface but not at the interface itself.

Particles chipped from corroded components are normally noticeably ferromagnetic and there is evidence showing that this is strongest in the intermediate zone where presumably the material is sufficiently nickel-rich to produce this effect.

IV. POSTULATED MECHANISM OF ATTACK

It would appear that there are nearly as many postulated mechanisms of sulfur attack as there are investigators in the field. However, the mechanism outlined below seems to enjoy fairly general acceptance and has been described by Betteridge (3) and also, in part, by Shirley (2).

The front of the attack consists of chromium sulfide (Cr_2S_3), the light gray globules detected on microscopic examination, dispersed in the parent material. Oxidation occurs to produce an intermediate layer of chromium oxide dispersed in nearly pure nickel, hence the ferromagnetism of the corrosion product. The outer layer appears to be a scale of nickel oxide, chromium oxide and the spinel, nickel chromite. With a continuous supply of sulfur, the nickel in the intermediate layer may be attacked to produce a low melting point (1190 F) nickel/nickel sulfide eutectic which can exude out.

Many investigators in this field believe that a requisite for the initiation of the attack is that the film of chromium oxide on the surface, assumed to act as a protective barrier to sub-surface attack, should be broken down. This suggests that a reducing agent must be present. Unburned carbon could act to reduce the chromium oxide. If the sulfur is present in the form of a sulfate, which is relatively non-reactive, carbon could reduce this to the more reactive sulfide.

Shirley (2) has shown in his work that the attack is not related to direct sulfur absorption from gaseous combustion products but does occur through contact with chloride-contaminated alkali and alkaline earth sulfates,

such as are present in sea salt. As little as 1.0 per cent chloride was found to induce a high rate of attack at 1300-1380 F. Considerably less attack was observed in the absence of chlorides.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

Previous studies (4) of high temperature corrosion of superalloys conducted in the Phillips 2-Inch Research Combustor facility have shown little or no effect of as much as 1.0 per cent sulfur in the fuel and rather copious quantities of ingested synthetic sea water. Yet both verbal and written reports of a severe form of sulfur corrosion known colloquially as "black plague" continue to appear. As mentioned above, these reports generally assign large responsibility to the reducing effects of unburned carbon, from the standpoint of (1) possible destructive effect on protective chromium oxide surface films and (2) reduction of the relatively non-reactive sulfates to more reactive sulfides. It has also been suggested by some that sulfurous combustion gases might also be reduced by carbon to more reactive species. Therefore, the present tests were designed with two objectives in mind: (1) to reproduce the type of attack described by other investigators in order to afford a better understanding of its nature and the degree to which it may take place under very severe conditions, and (2) to assess the relative importance of the several factors postulated as responsible for the attack; namely, unburned carbon, ingested sea salts and/or fuel sulfur contamination.

Table I shows the metal loss data obtained. Table II reports the visual appearance of scale formed and a visual estimate of the degree of attack. Table III is a tabulation of the magnetic properties of each specimen before and after exposure at 2000 F to the indicated combinations of reactant variables.

The first objective of reproducing the type of attack described by others as "black plague" was accomplished in the present work. When appreciable attack of the alloys was observed it fit quite well the descriptions outlined in the literature, as may be seen from an inspection of Table II. There are, however, some apparent discrepancies in the metal loss data shown in Table I when a comparison is made with the visual ratings of Table II. In several cases (a good example is Udimet 500 with air + carbon + SO_2) very severe attack was observed visually, while the metal losses were rather small. In these cases, re-examination of the descaled strips indicates that probably much of the damaged material was not removed by the wire brush descaling method utilized in these tests, suggesting that, in future work, careful consideration should be given to other techniques such as cathodic descaling in molten caustic. In any case, these results point out the dangers of drawing conclusions on the basis of metal loss alone when attack as extensive as observed in many of these tests has occurred. Certainly, when metal losses were high the visual ratings indicated very severe attack, but the converse was not always true. It is believed that the results of this series of tests confirm the potentiality of extremely severe attack causing catastrophic failures.

Considering the results in terms of the relative importance of carbon, sulfur dioxide and sea salt it may be seen from Tables I and II that, on an individual basis, only sea salt caused any significant attack relative to the "air only" baseline. Sulfur dioxide did show some tendency to cause increased corrosion, although this was very slight compared to the sharp increases in attack experienced during the air + sea salt runs. In this case, as in others to be discussed, the effect of sea salt was quite specific to certain alloys. René 41, for example, was almost completely destroyed during the air + sea salt run, while Udimet 500 showed only slight to medium attack.

The detrimental effect of the presence of carbon as a postulated reducing agent for protective chromium oxide films was confirmed in the tests with air + carbon + sulfur dioxide. Although neither carbon nor sulfur dioxide, by themselves, appeared significantly detrimental, together they brought about severe to very severe attack of all of the alloys. An interesting aspect of these tests is the fact that the metal losses generally did not reflect the severity of corrosion. The surface scale produced during these runs appeared to be loose, flaky and thick, but attempts to remove this scale showed that much of the sub-surface scale was actually adherent. Although extensive damage had been done, particularly to Udimet 500, as shown by the badly distorted surfaces, the metal losses did not reveal this because of the adherence of some of the corrosion product. It was also obvious that the greatest damage occurred over areas that were in direct contact with carbon.

Carbon also showed a tendency to accelerate sea salt corrosion as shown by the air + carbon + sea salt data in Tables I and II on Waspalloy, Hastelloy R-235 and Udimet 500. However, there were two exceptions, René 41 and Haynes Alloy 25, which indicated very pronounced inhibition attributable to the carbon. This was most apparent on a metal loss basis. Even so, the condition of the René 41 test strip was still considered as representative of catastrophic failure following the test with carbon and sea salt.

When sulfur was provided by both sulfur dioxide and sea salts (no carbon) results varied from mild acceleration by the added SO_2 in the case of Udimet 500 to apparent pronounced inhibition of the sea salt corrosion with René 41 (although the R-41 was still badly corroded). At this point it should be noted that inhbitition of the sea salt attack on René 41 was indicated for both sulfur dioxide and carbon. This was also true to a lesser extent in the case of Haynes Alloy 25. The reason for this effect is not obvious from the composition of these alloys, but it was, nevertheless, again borne out when

carbon was added while supplying both sea salts and sulfur dioxide. In these tests attack was definitely accelerated by the carbon, except in the case of René 41 where, again, the attack was apparently inhibited by both carbon and sulfur dioxide. Except for René 41, this combination of corrodents, air + carbon + sulfur dioxide + sea salt, was the most severe condition investigated, the balance of the alloys suffering catastrophic corrosion (approaching complete disintegration).

Of the forty tests involved in this program by far the most spectacular results occurred in the test where René 41 was exposed to air + sea salt. It seems desirable at this point to emphasize the fact that approximately 40 per cent of the original weight of the test specimen was lost in this test, showing the potential effect this single corrodent could have on certain alloys in jet engine "hot section" components without the presence of either unburned carbon or fuel sulfur.

With respect to the relative performance of the five alloys tested, these data show that no single alloy performed well in all situations. Overall, however, Udimet 500 performed best of the group.

Before and after exposure in the furnace each strip was checked for ferromagnetic properties after descaling. None of the metals exhibited appreciable magnetic properties before exposure, or after exposure to air, air + carbon, air + sulfur dioxide or air + sea salt. All except René 41 (which remained consistently non-magnetic) were strongly magnetic following exposure to air + carbon + sulfur dioxide and the property was most pronounced in the areas of the strips that were most severely corroded. Exactly the same results were observed in the tests with air + carbon+sulfur dioxide + sea salts, but with air + sulfur dioxide + sea salt only two alloys, Hastelloy R-235 and Udimet 500, became magnetic. With air + carbon + sea salt all of the materials

remained non-magnetic. Although there seem to be some inconsistencies in these data, sulfur dioxide is the common factor in those tests in which magnetic properties developed in the alloys. Checks for magnetic properties in samples of the scales removed from each strip showed that all were non-magnetic.

The interesting thing about these data is that, contrary to the findings of other investigators, the remaining metal rather than the scale became magnetic, suggesting that the metal had become enriched in magnetic elements such as nickel and/or cobalt by virtue of losses in the non-magnetic alloying elements as a result of corrosion. In other words, it would appear that nickel and/or cobalt were not attacked as much as some of the other alloying elements. This, of course, does not fit the previously outlined mechanism of attack postulated by many. It does, however, fit the results of earlier work conducted by Phillips (5) which has shown the importance of high nickel content in alloys exposed to high temperature sulfurous atmospheres.

V. CONCLUSIONS

The results of a series of six-hour 2000 F furnace tests on five typical current-generation superalloys, conducted to reproduce a type of corrosion known colloquially as "black plague" and to evaluate the relative importance of the several factors (unburned carbon, ingested sea salts and/or fuel sulfur contamination) postulated in the literature as responsible for the attack, have shown the following:

1. When appreciable attack of the alloys was observed it fit quite well the descriptions outlined by other investigators, indicating that "black plague" had been reproduced by these means.
2. Metal loss was not always a reliable index to degree of attack. When metal losses were high the visual ratings indicated very severe attack,

but the converse was not always true.

3. It would appear desirable, in future tests, to employ electrochemical descaling other than rotary wire brush descaling.

4. This series of tests confirms the potentiality of extremely severe attack - in fact, catastrophic failure.

5. On an individual basis only sea salt caused any significant attack relative to the "air only" baseline.

6. The effect of sea salt alone and in combination with carbon and/or sulfur dioxide was found to be specific to certain alloys. René 41 was almost completely destroyed during the air + sea salt run, while Udimet 500 showed only slight-to-medium attack.

7. The possible detrimental effect of carbon as a postulated reducing agent for protective chromium oxide films was confirmed in tests with air + carbon + sulfur dioxide. Although neither carbon nor sulfur dioxide by themselves were detrimental, together they brought about severe to very-severe attack of all of the alloys.

8. Carbon was found to accelerate sea salt corrosion of Waspalloy, Hastelloy R-235 and Udimet 500 while it markedly inhibited sea salt corrosion of René 41 and Haynes Alloy 25.

9. When sulfur was provided by both sea salts and sulfur dioxide (no carbon) results varied from mild acceleration by the added SO_2 with Udimet 500 to pronounced inhibition with René 41, although the R-41 was still badly corroded.

10. When carbon was included while supplying sulfur in the form of both sulfur dioxide and sea salts, the attack was definitely accelerated except in the case of René 41 where, again, the attack was apparently inhibited.

11. Except for René 41, the combination of air + carbon + sulfur dioxide + sea salt was the most severe condition investigated, the balance of the alloys suffering catastrophic corrosion.

12. Checks for magnetic properties in samples of scale removed from each test strip showed that all were non-magnetic.

13. Checks for magnetic properties in the test strips following furnace exposure showed that a number of them had become strongly magnetic, suggesting that the metal had become enriched in nickel and/or cobalt by virtue of losses in the non-magnetic alloying metals.

VI. OUTLINE OF PROJECTED WORK

Major modifications to permit preheating of the entire air capacity of the Phillips 2-Inch Research Combustor test facility to as high as 1400 F, permitting simulation of conditions for the most advanced engines and aircraft, are now complete and shakedown tests have been run. It is planned during the coming reporting period to extend previous six-hour metal loss tests on 1.0 per cent sulfur fuel to twelve hours. Additionally, it is planned to run a series of "black plague" turbine inlet guide vane corrosion tests using the two-inch combustor operating on a 1.0 per cent sulfur fuel containing 25 per cent (wt) aromatics while injecting sea water, thus providing reducing carbon by virtue of maximum specification aromatics content in the fuel, sulfur dioxide and sea salts. These tests will be run under cyclic conditions simulating a low-level tactical fighter mission consisting of 600 miles at Mach 1.2 and 200 miles at Mach 2.2. The total duration of each test will simulate six complete missions. Guide vane temperatures should range from 1550 F (M = 1.2 conditions) to 2000 F (M = 2.2 conditions) during these tests. No intermediate mechanical descaling will be done. The results of this series should provide information both on the

effects of extreme environmental conditions and the ability of current-generation superalloys to perform in such environments.

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TABLE I

EFFECT OF AIR, CARBON, SO_2 AND SEA SALTS ON TYPICAL SUPERALLOYS - METAL LOSSES IN SIX HOURS IN 2000 F FURNACE TESTS

Alloy	Metal Loss, mg — Treatment							
	Air	Air + Carbon	Air + SO_2	Air + Sea Salt	Air + Carbon + SO_2	Air + SO_2 + Sea Salt	Air + Carbon + Sea Salt	Air + Carbon + SO_2 + Sea Salt
Waspalloy	43	35	73	463 (1)	253 (2)	365	1850 (3)	2147 (3)
Hastelloy R-235	30	61	61	449 (1)	45 (2)	603	728 (3)	1178 (3)
René 41	33	8	79	4061 (3)	0 (2)	951 (2)	875 (3)	438 (1)
Haynes Alloy 25	28	31	86	1034 (2)	579 (2)	[illegible]23	329	1261 (3)
Udimet 500	14	54	72	209	75 (3)	396 (1)	719 (3)	892 (3)

NOTES:

(1) Visual rating after descaling: Medium - Very Severe

(2) Visual rating after descaling: Very Severe

(3) Visual rating after descaling: Very Severe, Catastrophic

TABLE II

EFFECT OF AIR, CARBON, SO_2 AND SEA SALTS AT 2000 F ON TYPICAL SUPERALLOYS - VISUAL APPEARANCE OF SCALE AND VISUAL ESTIMATES OF DEGREE OF ATTACK

Alloy	Treatment	Visual Appearance of Scale: Thickness*	Loose or Adherent?	Color	Blisters?	Surface Distortion**	Overall Visual Impression of Severity of Attack After Descaling**
Waspalloy	Air	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Carbon	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + SO_2	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Sea Salt	Thick	Loose	Gray-Black w/Green Areas	Yes	Medium - Very Severe	Medium - Very Severe, some localized craters.
	Air + Carbon + SO_2	Thick	Loose	Gray-Black w/Green Areas	Yes	Very Severe	Very Severe below carbon level, severe above carbon level.
	Air + SO_2 + Sea Salt	Medium	Loose	Green & Black	Yes	Slight - Medium	Slight - Medium
	Air + Carbon + Sea Salt	Very Thick	Loose	Green	Yes	Very Severe (Catastrophic)	Very Severe (Catastrophic), much localized cratering.
	Air + Carbon + SO_2 + Sea Salt	Very Thick	Loose	Black w/Green & Blue Areas	Yes (Very Severe)	Very Severe (Catastrophic)	Very Severe (Catastrophic), over entire strip.
Hastelloy R-235	Air	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Carbon	Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + SO_2	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Sea Salt	Medium	Loose	Green	Yes	Medium - Severe	Medium - Very severe, some localized crater areas.
	Air + Carbon + SO_2	Thick	Loose	Gray - Black	Yes	Very Severe - Slight	Very Severe below carbon level, Slight above carbon level.
	Air + SO_2 + Sea Salt	Thick	Loose	Black w/Blue & Peacock	Yes	Medium	Medium
	Air + Carbon + Sea Salt	Thick	Loose	Blue w/Peacock	Yes	Very Severe (Catastrophic)	Very Severe (Catastrophic), many large deep craters.
	Air + Carbon + SO_2 + Sea Salt	Very Thick	Loose	Black w/Green Areas	Yes (Very Severe)	Very Severe (Catastrophic)	Very Severe (Catastrophic) over entire strip.
René 41	Air	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Carbon	Thin	Adherent	Gray w/Green Areas	No	Very Slight	Very Slight
	Air + SO_2	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Sea Salt	Very Thick	Loose	Green	Yes (Very Severe)	Very Severe (Almost Destroyed)	Very Severe - Strip almost disintegrated, one end completely eaten away.
	Air + Carbon + SO_2	Medium	Loose	Gray-Black w/Green Areas	Yes	Severe	Severe below carbon level, Medium above carbon level.
	Air + SO_2 + Sea Salt	Thick	Loose	Gray-Black w/Green, Peacock	Yes	Severe - Very Severe	Very Severe over entire strip.
	Air + Carbon + Sea Salt	Very Thick	Loose	Black w/Peacock	Yes	Very Severe (Catastrophic)	Very Severe (Catastrophic), much localized cratering.
	Air + Carbon + SO_2 + Sea Salt	Very Thick	Loose	Black w/Peacock & Blue	Yes (Very Severe)	Severe	Medium - Severe over entire strip.
Haynes Alloy 25	Air	Very Thin	Adherent	Black	No	Very Slight	Very Slight
	Air + Carbon	Very Thin	Adherent	Black	No	Very Slight	Very Slight
	Air + SO_2	Very Thin	Adherent	Black	No	Medium	Slight - Medium
	Air + Sea Salt	Medium	Loose	Blue	Yes	Very Severe	Very Severe over entire strip, some crater areas.
	Air + Carbon + SO_2	Thick	Loose	Black w/Blue Areas	Yes	Very Severe	Very Severe below carbon level, Severe above carbon level.
	Air + SO_2 + Sea Salt	Thick	Loose	Black w/Blue Areas	Yes	Slight	Slight - Medium
	Air + Carbon + Sea Salt	Very Thick	Loose	Black w/Blue Areas	Yes	Medium	Medium
	Air + Carbon + SO_2 + Sea Salt	Very Thick	Loose	Black w/Blue Areas	Yes (Very Severe)	Very Severe	Very Severe (Catastrophic) over entire strip.
Udimet 500	Air	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Carbon	Thin	Adherent	Gray	No	Very Slight	Slight below carbon level, Very slight above carbon level.
	Air + SO_2	Very Thin	Adherent	Gray	No	Very Slight	Very Slight
	Air + Sea Salt	Thick	Loose	Gray-Black w/Green Areas	Yes	Slight - Medium	Slight - Medium
	Air + Carbon + SO_2	Thick	Loose	Black	Yes	Very Severe (Catastrophic)	Very Severe (Catastrophic) over entire strip.
	Air + SO_2 + Sea Salt	Medium	Loose	Gray-Black w/Green Areas	Yes	Medium-- Severe	Medium below salt level, Severe above salt level.
	Air + Carbon + Sea Salt	Thick	Loose	Green	Yes	Slight - Very Severe	Very Severe (Catastrophic), much localized cratering.
	Air + Carbon + SO_2 + Sea Salt	Very Thick	Loose	Gray w/Peacock, Green, Blue	Yes (Very Severe)	Very Severe (Catastrophic)	Very Severe (Catastrophic) over entire strip.

* Ratings may be very thin, thin, medium, thick, very thick.
** Ratings may be very slight, slight, medium, severe, very severe.

TABLE III

MAGNETIC PROPERTIES OF SUPERALLOYS BEFORE AND AFTER FURNACE TESTING AT 2000 F

Alloy	Before Exposure	Treatment							
		Air	Air + Carbon	Air + SO_2	Air + Sea Salt	Air + Carbon + SO_2	Air + SO_2 + Sea Salt	Air + Carbon + Sea Salt	Air + Carbon + SO_2 + Sea Salt
Waspalloy	NM	NM	NM	NM	NM	M	NM	NM	M
Hastelloy R-235	NM	NM	NM	NM	NM	M	M	NM	M
René 41	NM	NM	NM	NM	NM	NM	NM	NM	NM
Haynes Alloy 25	NM	NM	NM	NM	NM	M	NM	NM	M
Udimet 500	NM	NM	NM	NM	NM	M	M	NM	M

Code: NM = non-magnetic or so slightly magnetic as to be negligible.

M = magnetic.